# The sensitivity of African wave disturbances to remote forcing

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ABSTRACT

Ensembles of three simulations each, forced by June-September 1987 and 1988 sea-surface temperatures (SST) respectively, were made with a new version of the general circulation model of the NASA/Goddard Institute for Space Studies. Time series of 6-h meridional winds at about 780 mb over West Africa were spectrally analyzed to detect African wave disturbances whose properties for the two ensembles are compared and contrasted. The realistically simulated stronger 1988 Tropical Easterly Jet and the associated stronger upper-tropospheric divergence are components of interannual differences in the SST-forced planetary circulation, which correspond to higher amplitudes of African wave activity and concomitant excesses in 1988 Sahel rainfall rates. Results do not show, however, that most of the heavier precipitation was spatially organized by African wave structures. The excess rainfall is associated with stronger mean southerly circulation in the lower troposphere which carried more moisture into the Sahel. Nevertheless, because waves modulate winds, convergence, humidity and precipitation, the study suggests that they serve as a teleconnection mechanism whereby extreme Pacific Ocean SST anomalies are able to influence climate.

**1. Introduction**

   Links have been demonstrated between interannual variations of sea-surface temperature (SST) and seasonal precipitation accumulations over the Sahel by a number of studies (Lough, 1986; Folland et al., 1986; Druyan, 1987; Rowell et al., 1992). Indications are that deficits in Sahel precipitation occur when there are large areas of positive SST anomalies (SSTA) in Southern Hemisphere oceans and the Indian Ocean combined with negative SSTA in the Northern Hemisphere oceans, and in particular in the subtropical North Atlantic Ocean. In addition, many seasons with abundant rain in the Sahel can be associated with SSTA of opposite sign, especially in the Atlantic Ocean (Lamb and Peppler, 1992). The history of rainfall fluctuations over tropical Africa was described by Nicholson (1988), while Druyan (1989) and Lamb and Peppler (1991) reviewed a range of investigations related to the climate controls that influence sub-Saharan drought.

   Results of Palmer's (1986) general circulation model (GCM) experiments implied that Atlantic and Pacific Ocean SSTA had comparable impacts on Sahelian rainfall during the years his study sampled, while Folland et al. (1989) found that the forcing provided by global SST coverage achieved a higher correlation (r=0.70) between observed and modeled Sahel monthly mean rainfall than the forcing provided by only the tropical oceans (r=0.55). There are, therefore, notable exceptions for which extreme rainfall anomalies are not coincident with the occurrence of the documented drought and anti-drought SSTA "signatures" in the Atlantic. Thus, Palmer et al. (1992) found that the significant, positive 1988 minus 1987 Sahel rainfall differences were probably not forced by Atlantic SSTA, which were similar for both years. (The 1988 minus 1987 SST differences for June-August were less than 1°C over

most of the Atlantic between 30°N-30°S.) There is a strong suspicion that the Sahel droughts of 1983 and 1987 were much influenced by the extreme Pacific SSTA of those El Niño years (Lamb and Peppler, 1992; Palmer et al, 1992). On the other hand, the relatively rainy Sahel summer of 1988 occurred during a La Niña, characterized by SSTA some 3-4 °C cooler in the tropical Pacific than during the 1987 El Niño (see Fig. 1, Druyan and Hastenrath, 1994). The tele-connection mechanisms whereby remote SSTA bring about Sahel rainfall anomalies have yet to be analytically documented. The study described below examines certain aspects of the atmospheric response to the differential SST forcing of the 1987 and 1988 summers.

The association between African wave disturbances (AWD) and summer rainfall over the Sahel has been described in several observational studies (Reed et al., 1977; Payne and McGarry, 1977; Fortune, 1980), although deep convection is apparently not confined to only one part of the wave structure. Simulations with the Center for Ocean-Land-Atmosphere Studies GCM by Xue and Shukla (1993) showed westward propagating regions of heavy precipitation during August over northern Africa, presumably generated by wave disturbances. They found that replacing a realistic distribution of land surface types with desertified conditions (shrub with bare soil) over the entire Sahel caused a reduction in rainfall rates, but not in the number of disturbances during a given month. Their study therefore examined the rainfall "footprints" of AWD, but not the circulation structure of the phenomenon. Druyan and Hall (1994) (hereafter DH) demonstrated the feasibility of using the GCM of the NASA/Goddard Institute for Space Studies (GISS) to study especially circulations of AWD. We now build on the opportunities presented by the results in DH to investigate the role of AWD in the climate

variability of this region, and the importance of AWD as links in the teleconnections between ocean forcings and the West African climate.

The GCM used here is a greatly improved version of the GISS Model II (Hansen et al, 1983) used in DH, with nine vertical levels and 4°x5° horizontal resolution. The improvements in the moist convection scheme are described by Del Genio and Yao (1993) while the impact of several model changes on climate simulations is discussed by Marengo and Druyan (1994) and Druyan et al. (1995). The present study refers to six simulations using 1987 and 1988 SST and initialized from observed atmospheric conditions on 1, 2 and 3 June 1987 and 1988, respectively, which were combined into ensemble averages, called here ENS87 and ENS88.

## 2. Planetary circulation and the Tropical Easterly Jet (TEJ)

*a. Background*

Important features of the planetary circulation can be discerned from distributions of velocity potential (Trenberth, 1992) for which the isoline gradients are proportional to the magnitude of the irrotational component of the local wind. Maps of June-August velocity potential for ENS87 and ENS88 7th layer (≈200 mb) winds are shown in Fig. 1. Many features show good agreement with the corresponding fields based on ECMWF- analyzed 200 mb winds (see Palmer et al., 1992; Druyan and Hastenrath, 1994): a dipole pattern of negative values over the Western Pacific and Indian Ocean, representing the outflow associated with the Asian-African summer monsoon, and positive values over the Eastern South Pacific, South America and the South Atlantic Oceans, corresponding to convergence over the subtropical anticy-

clones of the winter hemisphere. The minimum is more extreme and was analyzed to be further west in 1988 than in 1987. Moreover, the ridge of maximum values in 1988 is also more pronounced than in 1987, indicating that the stronger upper-tropospheric divergence in 1988 over South Asia was juxtaposed with considerable upper-tropospheric convergence over the near-surface anticyclone accompanying anomalously cold SST in 1988 over the Eastern Pacific. A consequence of the stronger dipole in 1988 is the stronger gradient of velocity potential over Northern Africa (indicative of stronger irrotational circulation than in 1987). This is the location during boreal summer of the western end of a swift current of upper tropospheric easterlies, called the Tropical Easterly Jet (TEJ). The TEJ is the upper branch of part of a system of circulation cells in the zonal plane which circumscribe the entire globe at tropical latitudes (Hastenrath, 1988). These zonal circulations (or sometimes just the Pacific component) are referred to as the Walker circulation.

The reasonably realistic simulation of the June-August 1988 versus 1987 differences in the 200 mb velocity potential (Fig. 1), forced by the corresponding global SST distributions, suggests that the observed differences in the strength of the TEJ over Africa are caused by global SST differences. However, the Atlantic Ocean may have had a more minor role than the tropical Pacific, as discussed above.

Several studies have suggested that regions of positive vertical motion in areas of deep convection over West Africa are related to divergence at 200 mb (Reed et al., 1977; Duvel,1990). However, we do not know to what extent the excess upper tropospheric divergence is a consequence of the enhanced

convection and to what extent it has a role in stimulating additional convective rainfall. Reiter (1969) explained how upper tropospheric divergence should be generated by the positive vorticity advection (pva) associated with the left exit region of any jet, reasoning according to the vorticity equation. He concluded that the TEJ and its "traveling disturbances produce the high-level divergence fields that trigger... strong precipitation systems." Kidson (1977) found a high correlation between 200 mb wind speeds over 0°-15°N in August at 10°E and August rainfall along 15°N, 5°W-10°E, a finding consistent with Reiter's theoretical explanation since higher core speeds produce more pva and therefore more divergence. Similarly, Ratcliffe (1989a,b) reported that the TEJ of 1988 had recovered from its former weakness following the 1987 El Niño and precipitation over the Sahel in 1988 registered its first relatively rainy season in many years. Reed et al. (1977) and Duvel (1990) computed high-level divergence ahead of AWD troughs but whether this structure is exclusively the consequence of the dynamical feedback of convection is unknown. In summary, the physical processes producing the initial increases in upper tropospheric divergence and low-level convergence associated with AWD are unclear.

*b. ENS87 versus ENS88*

Figs. 2a and b show the modeled June-August 7th layer circulation over West Africa for ENS87 and ENS88, respectively, and Fig. 2c shows ENS88 minus ENS87 differences in the June-August means of the divergence of the two circulations. The TEJ is seen in Figs. 2a and 2b as a core of strong easterlies along 4-12°N, but speeds are as much as 6 ms$^{-1}$ higher for ENS88, corresponding to observed differences between these two seasons. Note that ENS88 isotachs are more zonal and parallel to the jet 's northern edge while ENS87 cir-

culation undergoes a very rapid westward deceleration over West Africa. The positive differences in Fig. 2c represent the greater ENS88 divergence located over most of West Africa, which is likely associated with the stronger TEJ of that season. Excess ENS88 divergence at 10-20°N corresponds to a change in the circulation from relatively straight to anticyclonic flow, and this veering of wind direction implies decreasing vorticity downstream and therefore divergence. It is not possible to separate divergence excesses resulting from the outflow above stronger 1988 convective towers from the stronger divergence caused by the interannual differences in large-scale circulation. However, that part of the excess ENS88 divergence that can be attributed to the stronger TEJ can accordingly be linked to the SST-forced differences in the planetary circulation discussed above.

Fig. 3a shows profiles of the monthly (June, July, August, September) means of ENS88 minus ENS87 differences in the zonal component of the 7th layer wind ($U_{200}$) along 5°E. It is clear that easterlies within the core of the TEJ (0-10°N) were stronger for ENS88 during each of the first three months and significantly so during June and July. For example, the July ENS88 minus ENS87 differences at 4°N and 8°N are about twice the standard deviation of $U_{200}$ for six runs using 1987 SST. Fig. 3b compares profiles along 5°E of the June-August means of $U_{200}$ for ENS87 and ENS88 with values from the corresponding ECMWF analyses. Although the modeled easterlies are consistently stronger than analyzed values, the relative strengths of the jets for the two seasons are consistent with the observational evidence. Profiles for the individual simulations of ENS87 and ENS88 for June-August (Fig. 3c) show a clear separation between the influence of 1987 global SST versus 1988 global SST forcing: easterlies between 20°N-10°S generated with the 1988 SST lower

boundary conditions were consistently stronger and cut a wider swath north and south of the TEJ axis. Moreover, the results from other model experiments suggest that 1988 initial conditions played a minor role, if any, in determining the summer means. We therefore interpret the foregoing model ensemble differences as a realistic representation of interannual variability.

**3. Spectral analysis of wave disturbances**

AWD were detected as local maxima between periods of 2-8 days in power spectra of time series of the 6-h mean meridional wind at model level 3 ($\approx$780 mb) over West Africa. The monthly average period of the disturbances thus defined ranged between 5.4-5.9 days. These mean periods do not show any systematic seasonality although isolated cases of 4-day peaks were evident in June. They compare more favorably with the empirical evidence (Reed et al., 1977) than those analyzed in DH for Model II, owing to a stronger mid-tropospheric jet, although periods are still about two days longer than observations indicate. Power spectra at 50-60% of the grid points within the area bounded by 8-24°N, 15°W-25°E show AWD activity in June-July, and 60-70% in August-September. This implied seasonality of AWD frequency may reflect the decrease over the summer of lower frequency variability (8-10- day periods) which can mask AWD peaks in June-July. After mid-summer, AWD spectral maxima become narrower and more discernable.

No systematic differences could be detected in the periods of the preferred spectral peaks between the power spectra of ENS87 and ENS88, but there were noteworthy ensemble differences in the locations and relative strength of wave activity. Fig. 4a shows that the June ENS88 runs produced higher spectral amplitudes (than ENS87 in the 4-6.4 day band) of simulated

AWD over West Africa along 20°N, east of 5°W, in contrast to lower spectral amplitudes further south and west. In July, a large area of excess ENS88 wave amplitudes can be seen along 5-10°W (Fig.4b). By August, the spatial distributions of wave activity create a pattern of positive ENS88 minus ENS87 differences over most of West Africa (Fig. 4c), dominated by the rather strong ENS88 amplitude maximum at 20°N,10°W in juxtaposition to the more southerly ENS87 maximum near 10°N,10°W. Results for September (Fig. 4d) show weaker waves in ENS88 over West Africa, except along the immediate Atlantic coast.

### 4. African Easterly Jet (AEJ)

Burpee (1972) attributed the generation of AWD to the vertical and horizontal wind shear created by the AEJ which forms during boreal summer near 600 mb along approximately 15°N over West Africa. During early summer the cool Atlantic monsoon air is thrust northward against the hot Sahara air mass, creating a strong meridional temperature gradient. The corresponding easterly thermal wind in the lower troposphere causes the near-surface westerlies to weaken with height and then reverse direction, reaching maximum easterly speeds of about 9 ms$^{-1}$ in the core of the AEJ between 600-700 mb.

Figs. 5a and 5b show cross sections of modeled June zonal wind speeds, averaged over the swath 15-5°W over West Africa for ENS87 and ENS88, respectively. The AEJ appears in June as a maximum at about 600 mb, and its configuration is somewhat different for ENS87 and ENS88. We have shaded areas on each cross-section where the usually positive meridional gradient of potential vorticity is negative, the criterion for the existence of instabilities

favorable for wave development (Charney and Stern, 1962; Burpee, 1972; DH). While both June 1987 and June 1988 show such instability in a region of high vertical wind shear beneath the core of the AEJ at 12°N, a second region appears at 20°N in June 1988, presumably a consequence of the greater horizontal wind shear. Cross-sections of the zonal wind for July (not shown) indicate a weaker AEJ for ENS88 at these longitudes, but stronger ENS88 mid-tropospheric winds closer to 20°N, 10°E. However, computations diagnose Charney-Stern instability for the July mean zonal circulation of *both* ensembles at 12°N *and* 20°N, east and west of the prime meridian. The August mean zonal wind speeds along 5-15°W (Fig. 5c, d) can be compared to observational analyses given by Burpee (1972) and Reed et al. (1977). Charney-Stern instability was minimal at 20°N in August for ENS87 (Fig. 5c) in contrast to its prominence on the ENS88 August cross-section (Fig. 5d). In this case, the instabilities, which correspond to the location of the ENS88 August maximum in wave amplitudes (Fig. 4c), can be attributed to the greater vertical and horizontal wind shears associated with the northern flank of the AEJ.

## 5. Precipitation

*a. Spatial distribution*

Palmer et al. (1992), Mo (1992) and Druyan and Hastenrath (1994) discussed the relative increases in summer precipitation over West Africa between 1987 and 1988. An analysis of June-August 1988 minus 1987 rainfall differences over West Africa from station data (Fig. 6a) shows 1988 excesses of 1-2 mm day$^{-1}$ which parallel the simulated ENS88 minus ENS87 differences (Fig. 6b). More than 50% of the ENS88 excess precipitation over the Western and Central Sahel (12-28°N, 20°W-15°E) occurred in July, 34% in June. Fig. 6c

shows the spatial distribution of ENS88 minus ENS87 precipitation rates for July. According to Palmer et al. (1992), July 1988 was indeed rainier than July 1987 over large expanses of West Africa . We note that, of the three maxima of ENS88 July precipitation excess: 22°N, 7°W; 10°N, 7°W; and 14°N, 17°E, the first two coincide with positive ENS88 minus ENS87 differences in spectral wave amplitude (Fig. 4b) and divergence of the 200 mb circulation (not shown for July). However, at the easternmost of these areas, ENS88 spectral wave amplitudes are distinctly lower than for ENS87 (Fig. 4b), emphasizing that AWD were not involved in the heavy rainfall. This is also evident in Fig. 7 which is discussed below.

*b. Longitude-time sections of rainfall*

Xue and Shukla (1993) considered time series of August rainfall over northern Africa simulated by the Center for Ocean-Land - Atmosphere Studies GCM and interpreted diagonal swaths of heavy precipitation as the "footprints" of westward propagating AWD. Fig. 7 shows daily precipitation rates greater than 4 mm day$^{-1}$ at 14-18°N for the six individual simulations of this study on similar longitude-time sections. Much of the summer precipitation is organized in diagonal bands indicating westward propagation of about 4-6° longitude per day, consistent with the 4-6 day period spectral peaks in the level-3 meridional wind. This graphical representation of the modeled rainfall over the Sahel shows a mixture of precipitation patterns. Occasionally, isolated narrow bands indicate that rainfall is exclusively associated with westward moving disturbances while diagonal "footprints" of very heavy rates are sometimes imbedded within wide areas of lighter rainfall. However, Fig. 7 also shows evidence of extended periods of significant rainfall which is

quasi-stationary as well as brief periods of zonally-oriented precipitation bands.

Shaded areas on Fig. 7 indicate the presence of a southerly wind component at model level 2 and diagonal streaks mark westward propagating waves, as in the case of precipitation. We note that many such streaks coincide with banded rainfall maxima while others are not associated with heavy precipitation at all. There are also examples of rainbands running parallel to the swaths of southerly wind, but preceeding them by several days. Southerly winds are more frequent than northerlies during the quasi-stationary and zonally-oriented precipitation episodes, indicating the circulation favored for positive moisture advection in the lower-troposphere.

Given the mixture of rainfall patterns which appear on the time-longitude sections, identification of wave-modulated precipitation is not entirely objective. We nevertheless found it instructive to estimate the frequencies of banded precipitation patterns that can be interpreted as consequences of wave activity. According to our estimates, 14 (42%) of the 33 occurrences are during August and 10 (30%) during July. The rainier 1988 ensemble had only about 3 (9%) more wave-propagated rainbands than 1987. Similarly, Xue and Shukla (1993) reported that their simulations of rainy Sahel summers consisted of approximately the same numbers of AWD as their modeled dry seasons.

Fig. 7 also shows that much of the heavy rainfall during June-July 1988 occurred in non-propagating structures between 0-20°E and concurrent with rather persistent southerly winds. In fact, the mean June-July 1988 minus 1987 positive precipitation differences coincide with positive differences in the

lower-tropospheric meridional circulation, implying stronger or more consistent northward advection of moisture into the Sahel.

## 6. Wave composites

Wave composites for 5°W and 5°E were constructed for the first and second halves of the summer following our method in DH. Here they are based on the time series of the 2nd layer ($\approx$890 mb) meridional wind component ($v$) at 16°N, filtered for the 4-6.4 day period. Individual waves, defined by the consecutive maxima of $v$ within each series, were further segmented into eight equal time intervals, representing different wave categories. Properties of composite waves were computed by averaging each wind component, precipitation rate, divergence and precipitable water (pw) for the same category interval over all waves in time series from all six simulations at grid elements along the same longitude. Wave composites of 890 mb wind vectors and divergence, 200 mb divergence, pw and precipitation (computed at 2.5° longitude westward displacement from winds) are shown in Fig. 8, where the maximum southerly wind at 16°N has been assigned to category 6.

Sharp north-south gradients in pw and precipitation rates characterize the Sahel region as a transition between the dry Sahara Desert to the north and the humid equatorial zone to the south. Perturbations of the generally zonal orientation of composite isohyets within this transition zone (12-20°N) can be interpreted as wave modulations of the precipitation pattern. The composites (Fig. 8) show lower-tropospheric convergence underneath upper-tropospheric divergence favoring the west sides of the troughs (categories 2-4). During June-July, there is evidence of precipitation enhancement near these areas of implied forced upward motion. However, during August-September,

similar areas of positive vertical motion are not within the wave categories that exhibit rainfall enhancement. Indeed, after mid-summer the stronger meridional circulation associated with the waves deforms the humidity field and promotes heavier precipitation east of the trough (category 6) by stronger south-to-north advection of moisture. We note that strong 200 mb divergence is associated with the region of lower-tropospheric convergence and not with the precipitation east of the trough, supporting the notion that upper-tropospheric divergence contributes to wave development and is not merely a passive consequence of deep convection. Fig. 8 also implies that, west of the trough, advection of drier air during August-September somewhat inhibits moist convection.

## 7. Discussion

Differences in the planetary circulation between June-August 1987 and 1988 were part of the atmospheric response to opposite phases of a significant ENSO episode. The GCM simulations discussed in this study were forced by observed SST during these two seasons and they capture many of the features of the contrasting planetary circulations which resulted, including the stronger TEJ in 1988.

Computations of the 200 mb divergence indicated higher monthly mean values over most of West Africa during June-August in the 1988 simulation. AWD composites included divergence maxima along wave axes or slightly to their west, even when this wave category did not favor heavy precipitation, implying that the origin of upper tropospheric divergence is often the dry circulation and not necessarily the deep moist convection. Since divergence results from the anticyclonic turning of upper-tropospheric air exit-

ing the jet above West Africa, the excess divergence computed for the 1988 simulations is consistent with and likely caused by the stronger TEJ, and therefore, at least in part, by the contrasts between the warm and cold phases of the 1987/88 ENSO episode. Excess divergence associated with the stronger TEJ, in turn, reinforced the structure of AWD by enhancing the upward motion concentrated near wave troughs (or to their west).

AWD were detected as peaks at 4-7 day periods in power spectra of 6-h meridional winds at 780 mb over 50-70% of West Africa between 15°W-25°E. Wave periods showed little seasonality and were substantially the same in the simulations for both years. However, the spatial distributions of wave (4-6.4 day period spectral) amplitudes were different over West Africa in the two simulations. During June and August, Charney-Stern instability was more pronounced near the ENS88 AEJ, suggesting that the mean circulation was more conducive to wave generation, although during July these instabilities were not clearly stronger for one or the other ensemble.

Longitude-time sections of modeled rainfall rates from individual simulations showed many heavy precipitation areas propagating westward synchronously with westward moving AWD. The longitude-time traces of the sign of the meridional wind as well as examination of the wave composites indicated that, especially during August and September, rainfall in the model was often enhanced by the southerly, moisture-laden winds of wave categories 5 and 6. However, we also found that a number of westward moving perturbations in the lower-tropospheric circulation organized rainfall closer to or west of (and prior to) wave axes, while yet others were not at all

accompanied by heavy rainfall. Moreover, there were several clear examples of heavy precipitation being simulated with minimal AWD influences.

The propagation of precipitation maxima by traversing AWD was most common in August followed by July, although it was also discernible during June and September as well. There were other examples, however, of stationary and simultaneous zonally-oriented rainbands. June-August 1988 experienced more Sahel rainfall, observed as well as modeled, but we found that only a proportion of the precipitation excess occurred where the wave activity was more vigorous.

## 8. Conclusions

Six four-month simulations with a new and improved version of the 4° x 5° horizontal resolution GISS GCM were used to study AWD climatology for the contrasting seasons of June-September 1987 and 1988. The results support the notion that rainy seasons in the Sahel do not experience a sharp increase in AWD numbers, but that excess rainfall may be associated with non-propagating mechanisms occasionally reinforced by passing wave structures. In the model, heavy precipitation was favored by low-level convergence near troughs during June/July and by the strong wave-modulated, moist southerly flow east of the troughs during August/September. Over select parts of West Africa, wave amplitudes were better developed under the stronger 200 mb divergence of 1988 and this probably increased the associated precipitation. However, the greater rainfall rates of the 1988 ensemble simulations did not appear to be attributable to wave-modulated patterns, which occurred in approximately equal frequency in both ensembles. The rainier conditions did coincide with stronger and more consistent southerly moisture advection

into the Sahel throughout the lower troposphere. Perhaps this stronger monsoon circulation is a direct consequence of the greater upper tropospheric divergence provided by the enhanced 1988 TEJ.

We have focused on the influences of Pacific Ocean SST anomalies on Sahel climate variability. Other forcing, notably Atlantic SST anomalies,  has been previously shown to have an important impact on Sahel seasonal rainfall during certain years, but was not a significant factor regarding 1987/1988. The present investigation found evidence that excess upper-tropospheric divergence from the stronger Tropical Easterly Jet in 1988 set the stage for the first relatively rainy season in the Sahel in more than a decade. The excess divergence was apparently not the passive consequence of copious deep moist convection. This role of TEJ-regulated divergence suggests that AWD enable fluctuations of the ENSO cycle to exert a remote influence on the interannual climate variability of the Sahel.

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FIGURES

Fig. 1. Velocity potential of modeled 7th layer ($\approx$200 mb) June-August circulation. a) ENS87 b) ENS88.

Fig. 2. Resultant wind vectors and mean isotachs (ms$^{-1}$) over West Africa for June-August  modeled 7th layer ($\approx$200 mb) circulation,
a) ENS87 b) ENS88 and c) the ENS88 minus ENS87 differences in the June-August mean divergence (x 10$^{-6}$ sec$^{-1}$).

Fig. 3. Latitude cross-sections of 7th layer ($\approx$200 mb) zonal winds (ms$^{-1}$) along 5°E over West Africa:
a) ENS88 minus ENS87, monthly b) modeled versus ECMWF analyzed June-August 1987 and 1988 means,
c) June-August means from individual simulations in ENS87 and ENS88.

Fig. 4. Spatial distributions of ENS88 minus ENS87 differences in the spectral amplitude of 3rd layer ($\approx$780mb) meridional winds (m s$^{-1}$) in the 4-6.4 day period band.  a) June, b) July, c) August and d) September.

Fig. 5. North-south cross-sections of modeled zonal wind (ms$^{-1}$) over West Africa, averaged over 15-5°W.
a) ENS87 June, b) ENS88 June, c) ENS87 August, d) ENS88 August
Shading indicates regions where the meridional gradient of potential vorticity (based on the zonal winds) is negative.

Fig. 6. The 1988 minus 1987 rainfall differences (mm day$^{-1}$): a) June-August observed (Mo, 1992), b) June-August modeled and c) July modeled.

Fig. 7. Longitude-time cross-sections of precipitation rates greater than 4 mm day$^{-1}$ for individual simulations at 14-18°N.  Contour interval is 4 mm day$^{-1}$. Shading indicates a positive (southerly) component of the model level 2 ($\approx$890 mb) wind.

Fig. 8. Wave composites along 5°W and 5°E for the first and second halves of the season, showing (from top to bottom): 2nd layer ($\approx$890 mb) circulation and divergence (x10$^{-6}$ sec$^{-1}$), 7th layer ($\approx$200 mb) divergence (x10$^{-6}$ sec$^{-1}$), vertically-integrated precipitable water (mm) and precipitation rates (mm day$^{-1}$).  The vertical coordinate refers to latitude in degrees from 16°N while the horizontal coordinate indicates wave category (see text).